AD-A181 745 POTENTIAL OBSERVING SYSTEMS FOR TROPICAL CYCLONE MOTION STUDIES(U) NAVAL POSTGRADUATE SCHOOL MONTEREY CA R L ELSBERRY MAY 87 NPS-63-87-003 1/1

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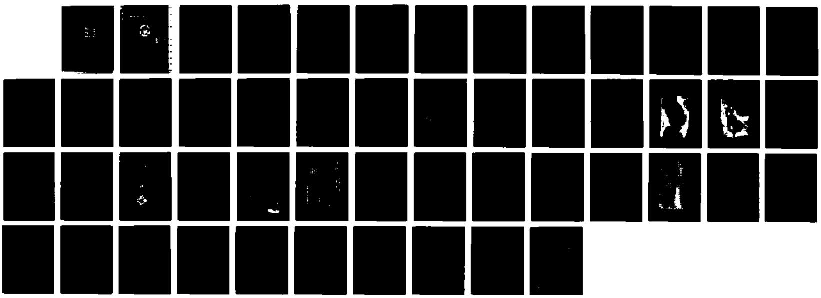

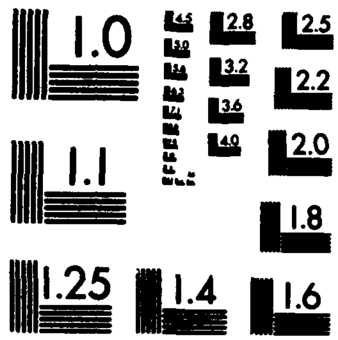

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Monterey, California

POTENTIAL OBSERVING SYSTEMS

FOR TROPICAL CYCLONE MOTION STUDIES

RUSSELL L. ELSBERRY

MAY 1987

Interim Report for Period October 1986-September 1987

Prepared for:
Chief of Naval Research (Code 1122MM)
Arlington, VA 22217

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The work reported herein was supported in part by the Office of Naval Research (Marine Meteorology) with funds provided by the Chief of Naval Research.

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Unclassified

SECURITY CLASSIFICATION OF THIS PAGE

A181 745

REPORT DOCUMENTATION PAGE

1a REPORT SECURITY CLASSIFICATION: Unclassified	1b RESTRICTIVE MARKINGS
2a SECURITY CLASSIFICATION AUTHORITY	3 DISTRIBUTION/AVAILABILITY OF REPORT: Approved for public release; distribution unlimited
2b DECLASSIFICATION/DOWNGRADING SCHEDULE	
4 PERFORMING ORGANIZATION REPORT NUMBER(S): NPS-63-87-003	5 MONITORING ORGANIZATION REPORT NUMBER(S)
6a NAME OF PERFORMING ORGANIZATION: Naval Postgraduate School; 6b OFFICE SYMBOL (If applicable)	7a NAME OF MONITORING ORGANIZATION
6c ADDRESS (City, State, and ZIP Code): Monterey, CA 93943-5000	7b ADDRESS (City, State, and ZIP Code)
8a NAME OF FUNDING/SPONSORING ORGANIZATION: Office of Naval Research; 8b OFFICE SYMBOL (If applicable): Code 1122MM	9 PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER: N0001487WR24029
8c ADDRESS (City, State, and ZIP Code): Arlington, VA 22217	10 SOURCE OF FUNDING NUMBERS: PROGRAM ELEMENT NO 61153N; PROJECT NO RR033-03-01; TASK NO; WORK UNIT ACCESSION NO

11 TITLE (Include Security Classification): POTENTIAL OBSERVING SYSTEMS FOR TROPICAL CYCLONE MOTION STUDIES

12 PERSONAL AUTHOR(S): Russell L. Elsberry

13a TYPE OF REPORT	13b TIME COVERED	14 DATE OF REPORT (Year, Month, Day)	15 PAGE COUNT
Interim	FROM 10/86 TO 9/87	1986 September	

16 SUPPLEMENTARY NOTATION

17 COSATI CODES			18 SUBJECT TERMS (Continue on reverse if necessary and identify by block number)
FIELD	GROUP	SUB-GROUP	Tropical cyclone motion; Tropical meteorology; Meteorological observations

19 ABSTRACT (Continue on reverse if necessary and identify by block number)

A synopsis is presented of a workshop during April 1987 sponsored jointly by the Hurricane Research Division (HRD) of the National Oceanographic and Atmospheric Administration (NOAA) and the Marine Meteorology Section of the Office of Naval Research (ONR). The objective of the workshop was to exchange information and begin documentation of observational systems that can be used in tropical cyclone studies. HRD personnel described the objectives of their annual field program studies and ONR personnel described plans for a field experiment on tropical cyclone motion during 1989 or 1990. Potential observational systems that were presented include: space-based systems; dropwindsondes; airborne radar systems; remotely-sensed surface wind speed systems; rawinsondes; wind profilers; and surface observations with drifting buoys. Recent HRD efforts to objectively analyze observations in the region of hurricanes were also described. Future plans for the ONR field experiment are briefly discussed. Keywords:

20 DISTRIBUTION/AVAILABILITY OF ABSTRACT: ☒ UNCLASSIFIED/UNLIMITED ☒ SAME AS RPT ☐ DTIC USERS	21 ABSTRACT SECURITY CLASSIFICATION: Unclassified	
22a NAME OF RESPONSIBLE INDIVIDUAL: Russell L. Elsberry	22b TELEPHONE (Include Area Code): (408) 646-2373	22c OFFICE SYMBOL: Code 63Es

DD FORM 1473, 84 MAR — 83 APR edition may be used until exhausted. All other editions are obsolete.

SECURITY CLASSIFICATION OF THIS PAGE

Unclassified

1. Background

During January 1987, a proposal for a workshop on observing systems for tropical cyclone research was made by representatives of the Office of Naval Research (ONR) Tropical Cyclone Motion Initiative. The Hurricane Research Division (HRD) agreed to host the workshop on 6 April to encourage participation by people attending the 17th Technical Conference on Hurricanes and Tropical Meteorology in Miami.

Dr. Stan Rosenthal opened the workshop (see agenda in Appendix A) by providing an overall review of the mission, program objectives and staff (about 40) of HRD. It was particularly appropriate for HRD to host such a workshop as they annually conduct observational studies in North Atlantic (and occasionally eastern North Pacific) hurricanes (Staff, HRD, 1987).

Dr. Bob Abbey, who is program director for Marine Meteorology of ONR, described the origin, motivation and present status of the Tropical Cyclone Motion Initiative. This Accelerated Research Initiative is a five-year program of basic research that began on 1 October 1986. In addition to theoretical and observational studies to improve basic understanding of tropical cyclone motion, this initiative includes a field experiment during 1989 (or 1990). Unfortunately, the recently announced decision to terminate aircraft reconnaissance in the western North Pacific tropical cyclones has introduced considerable uncertainty regarding the field experiment. Dr. Abbey presented four options that are being considered:

(i) That ONR seek additional funding (perhaps about $1 million) to replace the inner core observations that would have been achieved as part of the operational reconnaissance missions. Since the original funding for the initiative has already been reduced, and some further reductions are likely in the present financial situation, this option does not seen viable.

(ii) That the U.S. Air Force (USAF) be requested to provide substitute aircraft that could collect data in the environment of the tropical cyclone that would achieve some of the field experiment objectives. Preliminary discussions with USAF personnel indicate that such a request might be

favorably considered.

(iii) That the field experiment be shifted to the North Atlantic region to take advantage of the availability of aircraft resources of the Office of Aircraft Operations (OAO) of NOAA, satellite capabilities and other observational assets. Obviously, such a field experiment should be coordinated with the program of HRD.

(iv) That the field experimental component of the ONR initiative be cancelled and the funds be put into additional theoretical and observational research studies of tropical cyclone motion.

Dr. Abbey requested the advice of the participants (see list in Appendix B) in considering the field observation component.

2. Purpose of Workshop

The objectives of the workshop from the ONR viewpoint were two-fold: (i) Stimulation and exchange of ideas and approaches; and (ii) Preliminary documentation of the capabilities of observational systems that might be deployed in the ONR field experiment.

As indicated in Fig. 1, this workshop was just the first phase of a process that will lead to the execution of the field experiment. Two parallel paths are indicated in phases I and II. On the left are the tasks related to observational aspects. In phase I, the intent is to gather information on a broad spectrum of observing systems. In phase II, a more focussed study of specific observing systems will be carried out. Meanwhile, an examination of possible scientific hypotheses to be addressed in the field experiment has begun in phase I. The first step in this process was a Planning Meeting on the Theory of Tropical Cyclone Motion held in Monterey, CA during July 1986 (Elsberry, 1986). Studies based on existing data sets have also begun. It is expected that these theoretical and observational studies will indicate a number of possible hypotheses that will be narrowed to a smaller list during phase II.

Development of an experimental design plan in phase III (Fig. 1) will

PHASE	TASKS
I. EXPLORING POSSIBLE OBSERVING SYSTEMS	EXPLORING POSSIBLE SCIENTIFIC HYPOTHESES TO BE ADDRESSED
II. FOCUS ON SPECIFIC OBSERVING SYSTEMS	NARROWING OF HYPOTHESES

III. EXPERIMENTAL DESIGN PLAN

A. ESTABLISH LIST OF SCIENTIFIC QUESTIONS TO BE ANSWERED

B. MATCH OBSERVATIONAL REQUIREMENTS WITH SPECIFIC SYSTEMS

IV. OPERATIONS PLAN

V. EXECUTE EXPERIMENT

Fig. 1 Tasks during various phases in the ONR field experiment on tropical cyclone motion. The tasks in the left column during phases I and II are related to observational aspects, whereas those in the right column relate to formulation of scientific hypotheses based on ongoing theoretical and observational studies.

bring together the results of the studies in phases I and II. At this time, a specific list of scientific questions to be addressed in the field experiment will be established. At the same time, the observational systems and platforms required to measure the variables necessary to answer the scientific questions must be addressed in detail. The final planning step (phase IV in Fig. 1) prior to the field experiment will be an Operations Plan that will indicate the deployment of specific observation systems, the platforms that will be utilized in each phase of the experiment, and the procedures and/or flight plans that will be used to address the scientific hypotheses.

In summary, the first objective at this early stage in the planning for the ONR field experiment was to address the question "What variables is it now (or by 1989-90) possible to observe/measure in the tropical cyclone and its environment?" A synopsis of the potential observing systems discussed at the workshop will be presented in section 4. This information will be useful background when considering possible scientific hypotheses.

Another objective of the workshop was to explore possible cooperative studies between HRD and ONR personnel. It was useful at this stage to identify the interests of individuals in both groups. Hopefully, this will promote cooperation and avoid misunderstandings or conflicts.

As indicated above, the workshop was timed to take advantage of the presence of many scientists at the American Meteorological Society meeting. The ONR hopes to promote interest in this topic and to take advantage of this expertise. This workshop report is being circulated to inform others of the proceedings and to indicate opportunities to participate in future activities.

3. Planned observational studies

a. Hurricane Research Division

Dr. Bob Burpee described the objectives of the HRD observational program (see also Staff, HRD, 1987 for a more complete description of the observational and other programs at HRD). During 1987-1990, the emphases will be on: (i) Increasing HRD's data base for understanding hurricane motion and intensity changes; (ii) Improving knowledge of hurricane structure; and (iii) Providing better operational analyses of P-3 data to National Hurricane Center (NHC) forecasters.

(i) Synoptic-scale Environmental Flow Around Mature Hurricanes. This work is designed to investigate the steering currents on the periphery of mature hurricanes. The OAO's WP-3D aircraft are used to deploy Omega dropwindsondes (ODW) that measure horizontal winds, temperature, relative humidity and pressure. These ODW data are used in research studies and are transmitted in real-time to the NHC and the National Meteorological Center (NMC). The overall objective is to improve analyses and predictions of hurricane tracks.

(ii) Mesoscale Precipitation Features in Mature Hurricanes. The purpose of this research is the identification of the mesoscale and convective-scale features in mature hurricanes and the description of their basic organization and structure. A major effort has been to calculate the water budget in the eyewall region. Future work will focus on the microphysics (water content, liquid and ice particle concentrations and spectra, particle phase partitioning) in the convective and stratiform cloud regions of hurricanes. Understanding the microphysics is necessary to describe the way in which latent heat release on the cloud scale is transmitted upscale to the mesoscale circulations. Microphysical and radar reflectivity data have been used to

describe the characteristic structure of a supercell event in Hurricane Norbert.

(iii) Convective Rainbands in Hurricanes. The goal of this research is the description of the role of convective rainbands in hurricanes. Vertical cross-sections normal to rainbands have been constructed based on conventional and Doppler radar data plus flight-level observations. The kinematic structure of the convective rainbands and their modification of the larger scale wind field will be examined using the airborne Doppler data.

(iv) Vortex Motion and Dynamics. The goal is an improved understanding of hurricane motion, evolution and internal structure through detailed analysis of data from research aircraft and through formulation of relatively simple quasi-analytical models. Recent research flight data have substantiated a convective ring model that accounts for cyclic changes in hurricane intensity and eye size. A quasi-analytical model for the motion of a hurricane-like barotropic vortex has been formulated and tested (preliminary results had been presented by H. Willoughby at the Planning Meeting on the Theory of Tropical Cyclone Motion -- see Elsberry, 1986). Future extensions of the model will include treatment of baroclinic and nonlinear effects. Future plans include simultaneous observations from two aircraft at different altitudes to observe the matching between the vortex and its environment over a spatial domain of 300-400 km radius.

(v) Atmospheric and Oceanic Boundary Layer Dynamics. The goal of this research is to understand the structure and dynamics of the coupled atmospheric and oceanic boundary layers in the hurricane. New instrumentation is being tested in both media (see below). Exploitation of this instrumentation (including the second airborne Doppler radar that is scheduled to be available by September 1988) will allow a comprehensive energy budget study of the inner core of the hurricane.

(vi) Convective and Mesoscale Structure of Landfalling Hurricanes. The goal of this research is to describe the changes in magnitute/pattern of rainfall as the hurricane moves from open ocean to land. Statistical properties of the convective scale and mesoscale features of hurricane rainbands, and the life history and three-dimensional structure of the convection, is also being studied. The digital recording equipment being used in this activity is compatible with the NEXRAD systems to be deployed during the next few years.

A considerable improvement in the onboard computer systems of the WP-3D's will be exploited with several algorithms being developed. An objective analysis routine for flight-level data by Willoughby might be adapted for the onboard computer. With this routine, it would be possible to use the center-finding algorithm of Willoughby on the aircraft. Onboard analysis of the ODW data and transmission of more detailed ODW vertical sounding information are also possibilities. Other areas include radar-reflectivity composites, airborne Doppler wind fields and the remotely-sensed surface wind estimates. These algorithms will make the WP-3D's even more effective tools for tropical cyclone track research.

Finally, the HRD is exploring a cooperative program in 1988 with NASA/Goddard for coordinated flights with the NASA DC-8. This aircraft has the capability to observe well above the operating level of the WP-3D's.

b. ONR Initiative

LCDR Scott Sandgathe (USN), who was formerly the Deputy Director of the Joint Typhoon Warning Center (Guam), provided a perspective of the potential tropical cyclone track problems that might be addressed in a western North Pacific field experiment. Sandgathe grouped the cases into the following categories: (i) Cyclone-cyclone interaction; (ii) Cyclone interactions with adjacent synoptic-scale systems, including mid-latitude troughs, subtropical

ridges, monsoon surges and upper-level lows; (iii) Storm-related factors such as size, intensity and depth effects; (iv) Interactions with mountainous terrain; and (v) Extratropical transition. This list was ordered by priorities for operational track forecasts by Sandgathe, who provided examples of tracks and commentary on the difficulties that each type presented for forecasters. A more complete description of these cases is being prepared for publication by Sandgathe.

The occurrences of typhoons in the western North Pacific between July and November during 1959-85 are shown in Table 1. The average frequency is about three per month during July to October and then decreases to about 1.5 during November. Each October during the 27-y period had at least one typhoon. Only one July (1970), August (1977) and September (1960) had no typhoons during the entire month. However, four November's had no typhoons. There have been as many as eight typhoons in a single month (August 1960)! By contrast, the number of North Atlantic hurricanes during the last 15 y has been relatively low (only six named storms during 1986)! Since certain costs of mounting a field experiment are fixed, the absence of suitable cyclones to study represents an unrecoverable loss.

The occurrences of the various categories of western North Pacific tropical storms and typhoons listed above are given in Table 2. Certain phenomena are observed within limited periods. For example, tropical cyclone-interactions with the subtropical ridge circulations and the interactions with tropical upper tropospheric lows tended to be a summer and early autumn phenomena. Cyclone-cyclone interaction tends to occur in months with the highest frequency although two November cases occurred during this period. Storm interaction with midlatitude systems (46 cases) and terrain interaction (36 cases) are the most frequent occurrences.

YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	TOTALS
1959	0	0	0	1	0	0	1	5	3	3	2	2	17
1960	0	0	0	1	0	2	2	8	0	4	1	1	19
1961	0	0	1	0	2	1	3	3	5	3	1	1	20
1962	0	0	0	1	2	0	5	7	2	4	3	0	24
1963	0	0	0	1	1	2	3	3	3	4	0	2	19
1964	0	0	0	0	2	2	6	3	5	3	4	1	26
1965	1	0	0	1	2	2	4	3	5	2	1	0	21
1966	0	0	0	1	2	1	3	6	4	2	0	1	20
1967	0	0	1	1	0	1	3	4	4	3	3	0	20
1968	0	0	0	1	1	1	1	4	3	5	4	0	20
1969	1	0	0	1	0	0	2	3	2	3	1	0	13
1970	0	1	0	0	0	1	0	4	2	3	1	0	12
1971	0	0	0	3	1	2	6	3	5	3	1	0	24
1972	1	0	0	0	1	1	4	4	3	4	2	2	22
1973	0	0	0	0	0	0	4	2	2	4	0	0	12
1974	0	0	0	0	1	2	1	2	3	4	2	0	15
1975	1	0	0	0	0	0	1	3	4	3	2	0	14
1976	1	0	0	1	2	2	2	1	4	1	1	0	15
1977	0	0	0	0	0	0	3	0	2	3	2	1	11
1978	0	0	0	1	0	0	3	2	4	3	2	0	15
1979	1	0	1	1	0	0	2	2	3	2	1	1	14
1980	0	0	0	0	2	0	3	2	5	2	1	0	15
1981	0	0	1	0	0	2	2	2	4	1	2	2	16
1982	0	0	2	0	1	1	2	5	3	3	1	1	19
1983	0	0	0	0	0	0	3	2	1	4	2	0	12
1984	0	0	0	0	0	0	4	2	1	5	3	1	16
1985	0	0	0	0	1	2	1	5	3	4	0	1	17
AVERAGE	.2	.04	.2	.6	.8	.9	2.7	3.3	3.1	3.1	1.6	.6	17.3

Table 1. Occurrences of typhoons by months and year in the western North Pacific region during a 27-y period.

CASES	JUN	JUL	AUG	SEP	OCT	NOV	DEC	TOTAL
STORM - STORM INTERACTION	-	1	5	2	1	2	-	11
STORM - MIDLATITUDE INTERACTION	2	9	11	7	10	5	2	46
STORM - SUBTROPICAL RIDGE INTERACTION	2	5	6	3	1	-	-	17
EXTRATROPICAL TRANSITION	3	3	6	6	6	1	1	26
TERRAIN INTERACTION	2	8	9	8	5	2	2	36
MONSOON SURGE INTERACTION	3	-	6	2	3	4	6	24
TUTT OR UPPER LOW INTERACTION	1	4	5	3	5	-	-	18
TOTAL TYPHOON/TS 1982 - 1985	8	13	22	16	20	10	6	95

Table 2 Occurrences of tropical storms and typhoons by months during 1982-85 in the categories of operationally significant scenarios (see text for details). As a single storm may be included as a case of more than phenomenon, the total number of cases is greater than the number of storms.

One of the questions being explored is the possibility of the WP-3D's being away from the Atlantic region during the hurricane season. During the peak Atlantic hurricane season (usually during August and September), these aircraft have been "on-call" as a back-up or a supplement to the USAF reconnaissance aircraft. However, six of these USAF aircraft will be equipped with improved instrumentation packages that should be adequate to meet the reconnaissance tasking as required by the National Hurricane Center. Nevertheless, it is unclear if the research aircraft will then be free from the back-up reconnaissance role. The statistics in Table 2 suggest that a western Pacific field experiment involving the WP-3D's would be feasible if they could be away from the Atlantic during October and November.

4. Synopsis of potential observing systems

a. Space-based systems

Chris Velden of the Space Science and Engineering Center at the University of Wisconsin summarized the present and future capabilities of the USA satellite observing system. He made use of a timely article by Shenk, Vonder Haar and Smith (1987) that discusses the topic for mesoscale and cyclone events. Unfortunately, this discussion is incomplete at this stage since it does not reflect the present and future capabilities of satellites from other nations (especially Japan).

The present suite of USA satellites is indicated in Table 3. Both the NOAA and DMSP series of polar orbiters are anticipated to be in a two-satellite configuration from now until 1990, although gaps in coverage may occur due to early failures. A two-GOES configuration was recently re-established after a long period with only one GOES. As the life-time of that GOES is very uncertain, a period with a single GOES might occur again before

Table 3 Present status and future launches anticipated prior to 1990 for the USA satellite system (provided by C. Velden).

System	Number in Orbit	Key instrument systems	Future launches
		POLAR ORBITERS	
NOAA	2	HIRS, MSU, AVHRR	3/88, 3/89, 3/90
DMSP	2	OLS, SSM/T, SSM/I	--
NIMBUS-7	1	SMMR, TOMS	--
		GEOSTATIONARY	
GOES	2	VISSR, VAS	11/89, 7/90

Acronyms

HIRS - High-resolution Infrared System

MSU - Microwave Sounding Unit

AVHRR - Advanced Very High Resolution Radiometer

DMSP - Defense Military Satellite Program

OLS - Operational Line Scanner

SSM/T - DMSP Passive Microwave Temperature Sounder

SSM/I - DMSP Microwave Imager

SMMR - Scanning Multichannel Microwave Radiometer

TOMS - Total Ozoner Mapping Spectrometer

VISSR - Visible and Infrared Spin Scan Radiometer

VAS - VISSR Atmospheric Sounder

the scheduled launch of an improved GOES in November 1989. The present dual GOES at 75°W and 135°W will provide coverage between 160°E to 20°W with overlapping coverage between 140°W and 70°W. A single GOES (located at 100°W) provides much more limited coverage, although the likely regions for a field experiment in western Atlantic (or eastern Pacific) hurricanes would be covered.

The observational guidelines for tropical cyclones in Table 4 from Shenk <u>et al</u>. (1987) can provide a <u>prototype</u> for a specification of the observational requirements in the ONR field experiment. However, many of the stringent spatial and temporal requirements with respect to the eye and the eye wall regions are more related to intensity prediction rather than motion prediction. A shift in the rankings of the most important variables is also likely, as the wind field is the crucial variable for motion studies.

A summary of the satellite-derived products, resolution and accuracies is given in Table 5. As indicated by Shenk <u>et al</u>. (1987), the polar orbiters generally provide better horizontal and vertical resolution than the geostationary satellites, which provide data over a large area with high temporal resolution. A polar orbiter generally provides data only twice a day within a swath of 600 - 1500 km width. The microwave instruments (polar orbiters only) can sense through clouds (except heavy rain areas), whereas the IR systems are limited to cloud-free areas. However, the horizontal resolution of the microwave devices is relatively coarse.

No significant improvements in polar orbiter capabilities are expected between now and 1990. However, a new generation GOES is expected to be launched in late 1989 (Table 3). This system will be able to image and sound in the vertical simultaneously. The IR imaging and sounding channels will be similar to present polar systems. Improvements in earth location, resolution,

Parameter	Resolution: Spatial (km)	Resolution: Vertical (km)	Resolution: Temporal	Absolute Accuracy
Temperature:				
Sea surface	20–100		6–24 h	±1.0 K[a]
Profiles				
1. Away from eye wall	40–200	1–5[b]	1–3 h	±1–1.5 K[c]
2. Eye and eye wall	5–50	1–5	10–60 min	±1–3 K[c]
Moisture profiles:				
1. Away from eye wall	20–100	1–5[b]	1–3 h	±5–15%
2. Eye and eye wall	5–50	1–5	10–60 min	±5–15%
Surface pressure:				
1. Away from eye wall	40–200		1–3 h	±1–3 mb
2. Eye and eye wall	5–50		10–60 min	±1–3 mb
Winds:				
Boundary layer	20–50	0.2–1	30–120 min	±1–3 $m \cdot s^{-1}$
Above boundary layer	40–150	1–5	1–3 h	±1–3 $m \cdot s^{-1}$
Precipitation:				
Rate	10–50		15–120 min	±20–50%
Yes/No	10–50		15–120 min	
Cloud Top Height	2–20	0.25	3–30 min	±500 m[a]

[a] Relative accuracy should be one-half of these values.
[b] 0.2 km through *inversions*.
[c] Relative accuracy ≤1.0 K.

Table 4 Observational requirements for prediction of tropical cyclones according to Shenk et al. (1987).

Table 5 Current products, capabilities and accuracies for satellite systems in Table 3 (provided by C. Velden).

System	Products	Resolution (km)	Accuracy
		POLAR ORBITERS	
NOAA-AVHRR	VIS/IR imagery	1 (horizontal)	--
-HIRS	T, q soundings	5 (vertical) 25 (horisontal)	1-2°K
-MSU	Rainfall Cyclone central pressure/intensity	110 (horizontal)	Factor of two 6-8 mb RMS, 10-15 kt RMS
-AVHRR	Sea-surface T	1 (horizontal)	1°K
DMSP-OLS	VIS/IR imagery	1 (horizontal)	--
-SSM/T	soundings	175 (horizontal)	~ 2°K
-SSM/I	Rainfall Cyclone central pressure/intensity	20 (horizontal)	5-15 mb RMS, 5-10 kt RMS
NIMBUS-SMMR	Imagery	25-125 (horizontal)	--
TOMS	Total ozone	?	?
		GEOSTATIONARY	
GOES-VISSR	VIS/IR imagery	1/4	--
	H_2O imagery	8	--
	Cloud drift winds	20-100	2-5 m/s
	Rainfall	Variable	Factor of 2-3 from gauge
	Cyclone central pressure/intensity	--	5-15 mb RMS, 5-10 kt RMS
	Sea-surface temp.	15	± 1 K absolute
-VAS	Multi-spectral imagery	8	--
	T, q soundings	30-90	± 2 K, ± 25% rel. hum.
	H_2O vapor winds	100-500	5-15 m/s

calibration and timeliness are expected. Unfortunately, this system will not be available until the 1990 tropical cyclone season, and only in the region of the USA. Further improvements in geostationary satellite sensing capability beyond this system are discussed by Shenk et al. (1987). It is emphasized again that the above discussion applies only to the USA region. Similar information and future plans will be sought from other nations. Preliminary information indicates that no VAS-type sounding capability and no water vapor imagery will be available on the Japanese Geostationary Meteorological Satellite (GMS) series before 1991. The next GMS satellite is virtually identical to the present one.

b. Dropwindsondes

The HRD has pioneered the use of Omega dropwindsonde's (ODW) launched from aircraft in the hurricane environment. James Franklin of HRD summarized the experience gained from these synoptic flow experiments. The ODW's provide a vertical sounding from flight-level (~ 400 mb typical elevation for WP-3D) to the surface. In addition to p, T and relative humidity (PTH), the winds are calculated from navigation signals from at least three Omega transmitters. The fall rate is ~ 1000 ft/min (25-30 mb/min), so a descent from 400 mb takes about 23 min. Since only three ODW's can be in the air simultaneously, the maximum drop frequency is about 9 min, which corresponds to a 45 n mi separation for a aircraft speed of 300 kt. A more reasonable pace for sustained deployments would be 60-90 n mi separation.

Given the 2600 n mi operating range of the WP-3D's, it is necessary to use two aircraft for a typical synoptic flow experiment (see Fig. 2). One of the recent modifications in these flight plans is to include a penetration of the hurricane center by at least one of the aircraft to provide inner core data to match with the synoptic flow observations in the analysis program

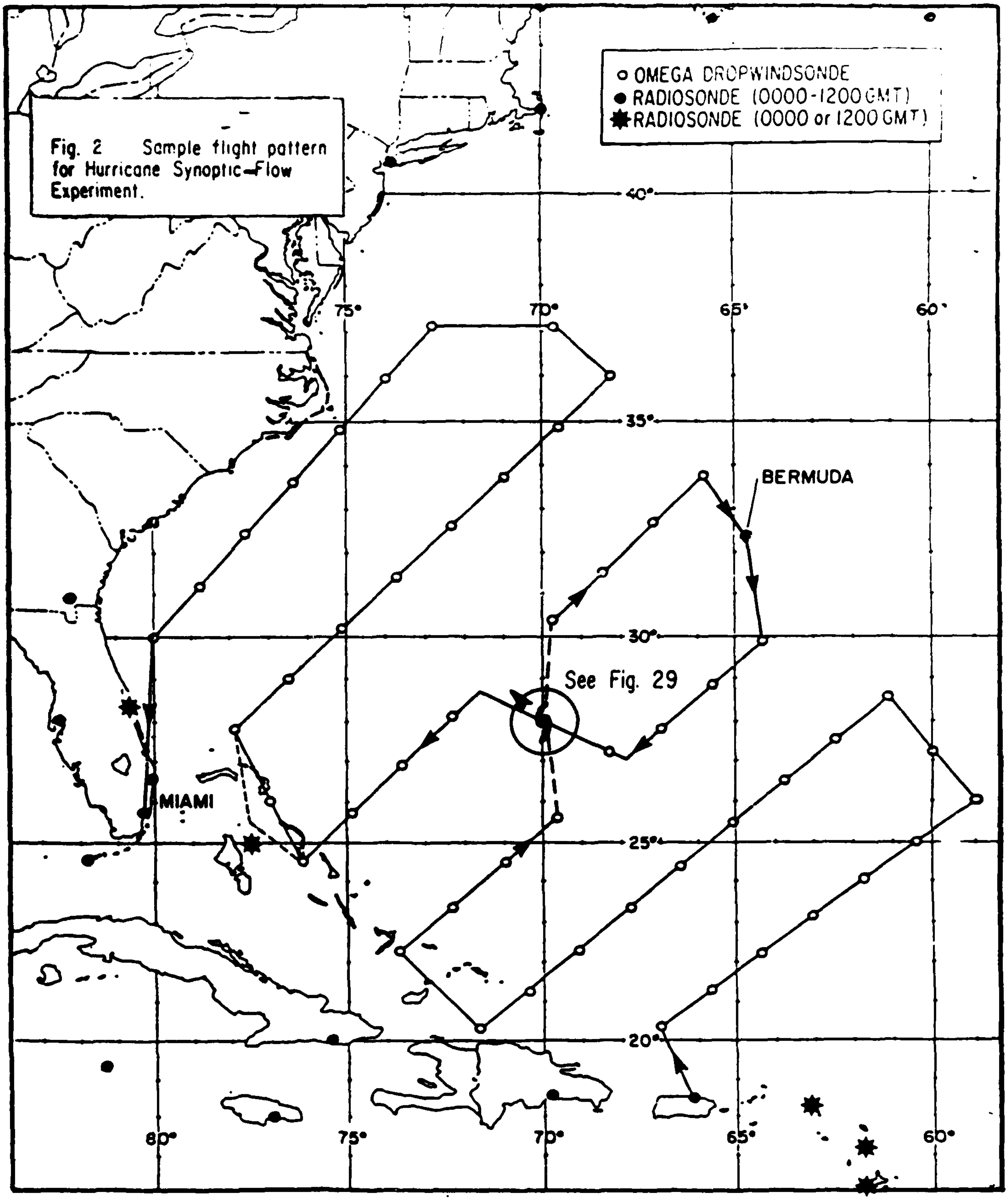

Fig. 2 Sample flight pattern for hurricane synoptic-flow experiment (provided by R. Burpee).

(see below).

The vertical interval for reporting PTH is 10 s ($\sim$ 5 mb) for real-time data and 1 s (0.5 mb) for post-processed data. However, post-processed PTH data are typically filtered with a 20 s cutoff and reported at 10 s intervals. The nominal accuracies for the ODW data are given in Table 6. However, the HRD finds the root-mean-square (RMS) surface pressure errors are about 5 mb. Only with a careful hydrostatic calculation is a 2 mb RMS error achieved. For the winds, the vertical resolution varies with signal quality. A typical ODW wind estimate represents a 50-75 mb layer-mean value. The necessity for vertical averaging means that reliable wind observations can not be obtained within 30-40 mb of the surface. HRD experience in the North Atlantic indicates typical wind accuracies of 1-2 m/s.

Franklin summarized the major limitations of the present ODW's: (i) cost of $650/ODW; (ii) occasional loss of T data in an extremely wet environment, so that the present sondes should not be deployed in convection; (iii) icing conditions on the aircraft occasionally results in loss of sonde signals; (iv) aircraft turns during an ODW descent can introduce wind errors of several m/s over a 50-75 mb layer (can be corrected in post-processing with WP-3D flight-level data); (v) humidity elements often dry out slowly below cloud layers; (vi) data are not available in digital form (this may be corrected by 1989); (vii) post-processing of ODW data (about $100/ODW) is essential for detailed diagnostic studies; and (viii) ODW's may only be deployed over the ocean (because of the weight) and with proper clearance of aircraft in the region.

Vin Lally of the National Center for Atmospheric Research (NCAR) summarized the dropwindsonde characteristics developed by that group (Table 7). The 1985 ODW is essentially the same as described above by Franklin. The 1987 version has been redesigned for digital operation (greater

Table 6 Accuracy of the Omega dropwindsondes (provided by J. Franklin).

Variable	Instrument	Nominal Accuracy (Range)
Pressure	Aneroid	± 2 mb
Temperature	Thermister	± 0.5°C (0 < T < 40°C)
Rel. Humidity	Carbon Hygristor	± 5% (>0°C) ± 8% (-20 < T < 0°C) ± 13% (-40 < T < -20°C)
Wind		1 m/s RMS (4 min averaging)

reliability and ease of operation), lighter weight and a reduction in cost. Further improvements are planned for the 1989 Experiment on Rapidly Intensifying Cyclones in the Atlantic (ERICA) sponsored by ONR. This will be light weight (300 g) and fast-falling, with winds derived from cross-chain Long-Range Navigation (LORAN) signals rather than from Omega navigation. Consequently, 300-600 m resolution in the vertical should be possible. Other improvements include a heated humidity element and a sea-surface temperature observation from an instrument deployed upon impact.

The wind errors to be expected from a sonde using the world-wide LORAN network are described by Passi and Morel (1986). Although this sonde will have acceptable wind errors off the east coast of the USA, unacceptable errors would occur in the Caribbean and north of Cuba and Puerto Rico (Fig. 3). Consequently, this sonde would not be useful for a hurricane experiment in this region. However, the wind errors in the western North Pacific region (Fig. 4) appear to be acceptably small.

Finally, a truly advanced dropwindsonde based on the Global Positioning System (GPS) will be available in 1990 (Table 7) when at least 12 navigational satellites will have been launched. This light-weight sonde will have only a small chute and will fall very rapidly (up to 30 m/s). Because of the

extremely accurate location capability (Table 8) with the GPS, the wind averaging layer can be very small (< 150 m). The anticipated wind accuracy is an incredible 1 cm/s with only 1 sec averaging (30 m vertical resolution). Consequently, wind observations will be possible to within a few meters of the sea surface. No pressure measurement (aneroid) will be necessary (Table 8) since the elevation of the sonde will be known so accurately. No restrictions on dropping such light-weight sondes will be required. Consequently, obtaining extremely accurate wind, T and relative humidity observations at relatively low cost from jet aircraft elevations to the surface will be possible in 1990.

Table 7 Characteristics of present and future NCAR dropwindsondes (provided by V. Lally).

	1985	1987	1989	1990
Mass (g)	1300	900	300	300
Fall rate (m/s)	12-6	12-6	20-10	30-15
Wind averaging layer (km)	2-1	2-1	0.6-0.3	0.15-0.075
Cost	$600	$300	$300	$300
Pressure element	Ceramic Aneroid	Aneriod	Aneroid	None
Transmitter (Watts)	1	2	1	10
Coding	Analog	Digital	Digital	Digital
Wind Computation	Omega	Omega	Loran	GPS*

*Global Positioning System

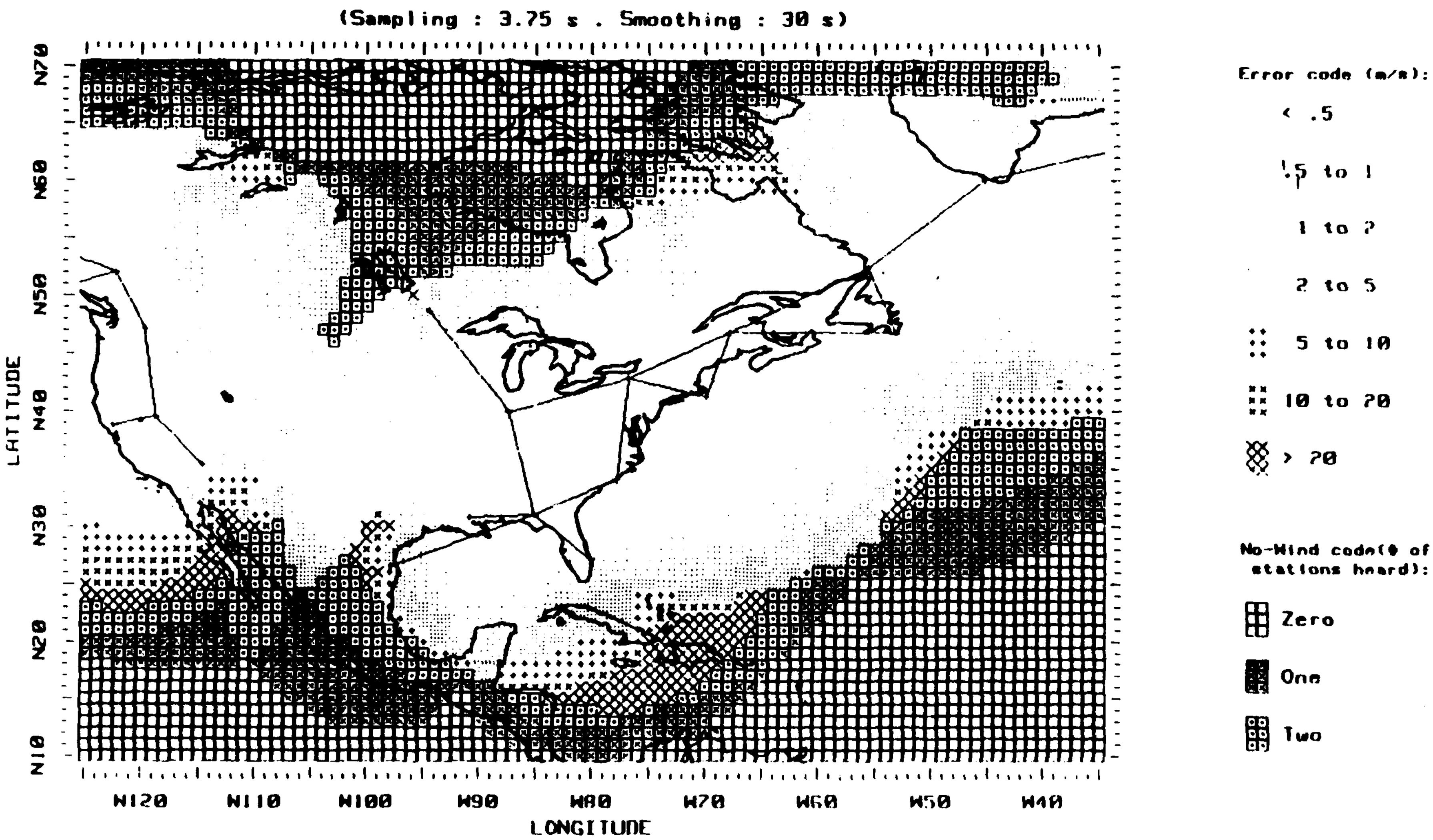

Fig. 3 Wind error classifications (see code on right) for CLASS soundings in the region of North America (provided by V. Lally).

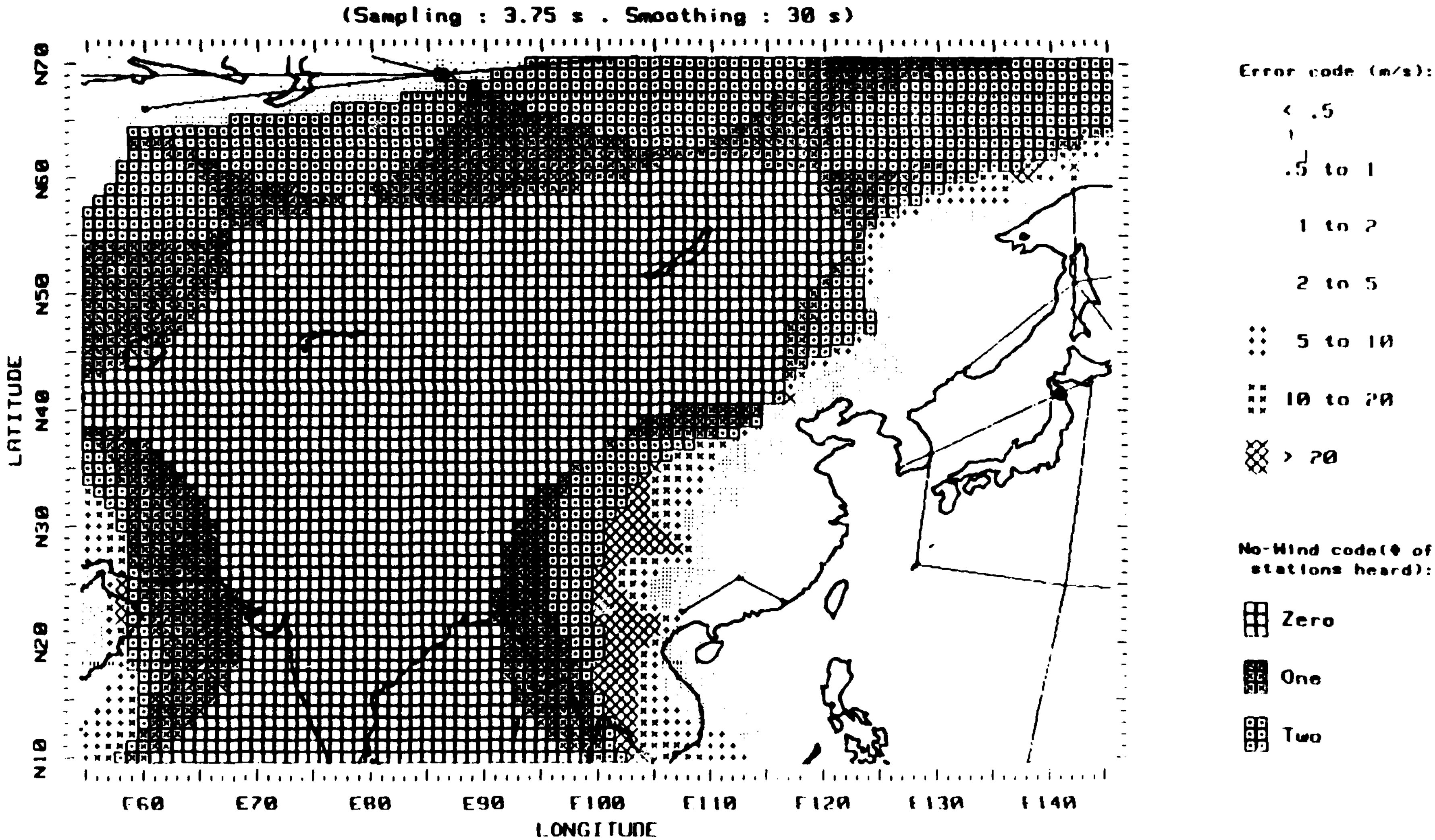

Fig. 4 Wind error classifications as in Fig. 3, except for Asian region (provided by V. Lally).

Table 8 Comparison of accuracies of Omega, LORAN and GPS dropwindsondes (provided by V. Lally).

	Absolute accuracy	Differential accuracy	Wind accuracy
Omega/VLF	2000 m	200 m	1-2 m/s (3 min avg.)
LORAN	200 m	20 m	< 1 m/s (30 sec avg.)
GPS	20 m (altitude) 10 m (lat/long)	1 cm	1 cm/s (1 s avg.)

c. Airborne Radar Systems

Frank Marks of HRD described the capabilities of the conventional and Doppler radars on the WP-3D (Table 9). The airborne Doppler radar mounted in the tail of one of the aircraft is a useful tool for estimating mesoscale air motion in precipitating systems such as hurricanes. With a 3.22 cm wavelength and a pulse repetition frequency of 1600 pulse/s, the unambiguous velocity interval is ± 12.9 m/s and the unambiguous range is 93.75 km. Velocities up to 60 m/s have been achieved by post-processing (using the known wind velocity at flight level). Attenuation due to rain particles may cause problems with this wavelength radar. Thus, the aircraft has to be positioned close to the area of interest.

As the range from the radar increases, the vertical structure of the wind field that can be detected is limited by the vertical beam width of 1.9° (Fig. 5). For example, the half-power points are separated by 2 km at only 60 km in range. The maximum range of Doppler data coverage with 150 m range gates is 39 km and with 300 m range gates is 78 km. The new airborne radar system (available in Fall 1988) will have a maximum range of 94 km. The scientist must choose the options and trade-offs that best fit the experiment design. The HRD recommendations for most mesoscale research are indicated by stars in the right column of Table 9. The angle between flight legs should be between 45° and 90° (Fig. 5). This V-or L-pattern allows calculation of "dual-Doppler" winds in

the overlap region since the radar detects only the radial component toward or away from the radar. The smaller the angle between the legs, the larger the area covered by dual-Doppler winds. However, the uncertainty in the horizontal wind estimate increases as the angle decreases, and a longer time in needed to complete the pattern. Angles between 60° and 90° are considered optimum. Other considerations for planning experiments are included in the "Airborne Doppler Radar Scientist Guide" available from F. Marks.

The primary consideration in the use of the lower fuselage (LF) radar (Table 9) is to select an operating altitude that will give a good radar presentation of the precipitation features. The major drawback of the LF radar is the large vertical beam width (4.1°). As indicated in Fig. 6, very little clearance exists between the beam and the rear portion of the aircraft fuselage. Since the aircraft normally flies in a nose-up attitude, and the beam is stabilized to be parallel to the earth's surface, beam blockage by the fuselage occurs toward the rear much of the time. Beam blockage, which is especially evident when flying at low altitudes, appears on the screen as a shadow behind the plane, or a fan of high reflectivity across an arc 30° wide. The second problem with the large vertical beam width is in the beam illumination of the targets, which depends critically on the orientation of the beam and the aircraft altitude. Marks (1985) shows the mean LF radar signal loss with range for four altitudes (Fig. 7). At larger ranges, the height of the center of the beam increases and more and more of the beam is unfilled, or filled with the less reflective portion of the storm. When the aircraft is at low altitude, the signal losses increase more rapidly with increasing range than when the aircraft is at high altitude. At high altitudes, the beam elevation is usually slightly depressed to illuminate the low altitude, strong reflectivity portion of the storm at larger ranges. However, flight levels above the bright band will cause low reflectivities in the beam close to the

Table 3 Characteristics of the NOAA WP-3D aircraft radar (provided by F. Marks).

Parameter		LF Radar	TA Radar	Doppler
Transmitter:	frequency	5.370 GHz	9.315 GHz	Same as TA
	wavelength	5.59 cm	3.22 cm	"
	pulse length	6.0 μs	0.5 μs	"
		(900 m)	(75 m)	"
	peak power	70.0 KW	60.0 KW	70.0 KW
Pulse repetition frequency		200 PPS	1600 PPS	Same as TA
Antenna:				
gain - main beam		37.5 dB	40 dB	"
gain - 1st sidelobe		-23 dB	-23 dB	"
stabilization		±10°	±25°	"
		(pitch/roll)	(pitch/drift)	"
	scan rate (min)	2 RPM	4 RPM*	"
	(max)	4 RPM	8 RPM	"
	polarization	linear(horiz.)	linear(vert.)	"
Beamwidth:	horizontal	1.1°	1.35°	" (at half-
	vertical	4.1°	1.90°	" power point)
Range gate interval		1.45 km	0.36 km	0.15 km* 0.30 km
Range delay		0 m	0 m	900 m (150 m gates)* 1200 m (300 m gates)
Maximum range		370.4 km	92.6 km	39.3 km (150 m gates)* 78.0 km (300 m gates)
No. samples averaged		15	63	32,* 64, 128, 256

* Recommended values for Doppler

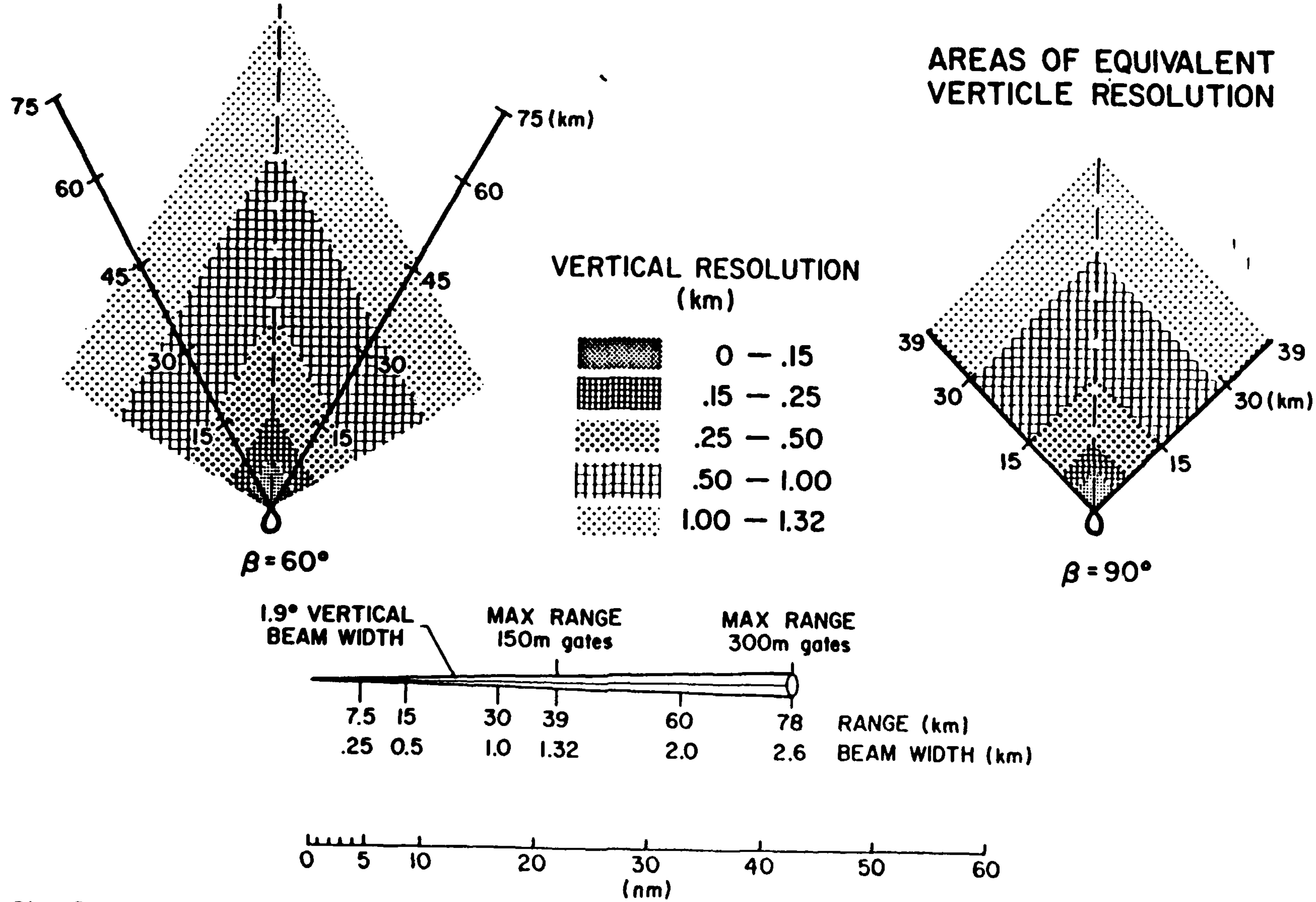

Fig. 5 Effects of vertical beam resolution as a function of range (bottom) and the areas of equivalent vertical resolution for the V-shaped flight plan (top, left) and L-shaped flight plans (top, right) normally used for "dual-Doppler" applications of the NOAA airborne radar (provided by F. Marks).

aircraft where the beam is still narrow. Consequently, a flight altitude below the bright band altitude (about 3 km) is best for LF coverage and detection.

d. Remotely-sensed Surface Wind Speeds

Dr. Peter Black of HRD discussed a number of airborne sensors. Perhaps the most relevant to the field experiment is the Stepped Frequency Microwave Radiometer (SFMR). This C-band (4.5 - 7 GHz) instrument is based on the strong correlation between passive microwave emission from the ocean and the surface wind speed. The radiometric emission, or brightness temperature, increases monotonically with wind speed because of the increased surface foaming and wave breaking. However, the amount of radiative emission received at aircraft flight level depends on the intervening atmospheric conditions (water vapor, clouds and precipitation). Emissions at two or more frequencies are compared to correct for attenuation due to rain rate, which depends upon frequency to some power in an exponential. Algorithms have been developed (Tanner, Swift and Black, 1987) to relate the received microwave radiation to the ocean surface wind speed. Since the SFMR can operate while penetrating cloud, data can be collected from aircraft flying at higher and safer altitudes than presently used. Since it will not be necessary for the flight meteorologists to see the surface wave conditions to make wind speed estimates, the passive microwave sensor will allow surface wind speed estimates during nighttime flights.

The SFMR surface wind estimates have been compared with moored buoy winds and aircraft flight-level winds. The standard deviation between the SFMR and buoy winds is about 1.4 m/s. Recommendations have been made to integrate the SFMR algorithm into the WP-3D aircraft data system for nearly instantaneous presentations of surface winds and rain rates (a byproduct of the atmospheric correction algorithm).

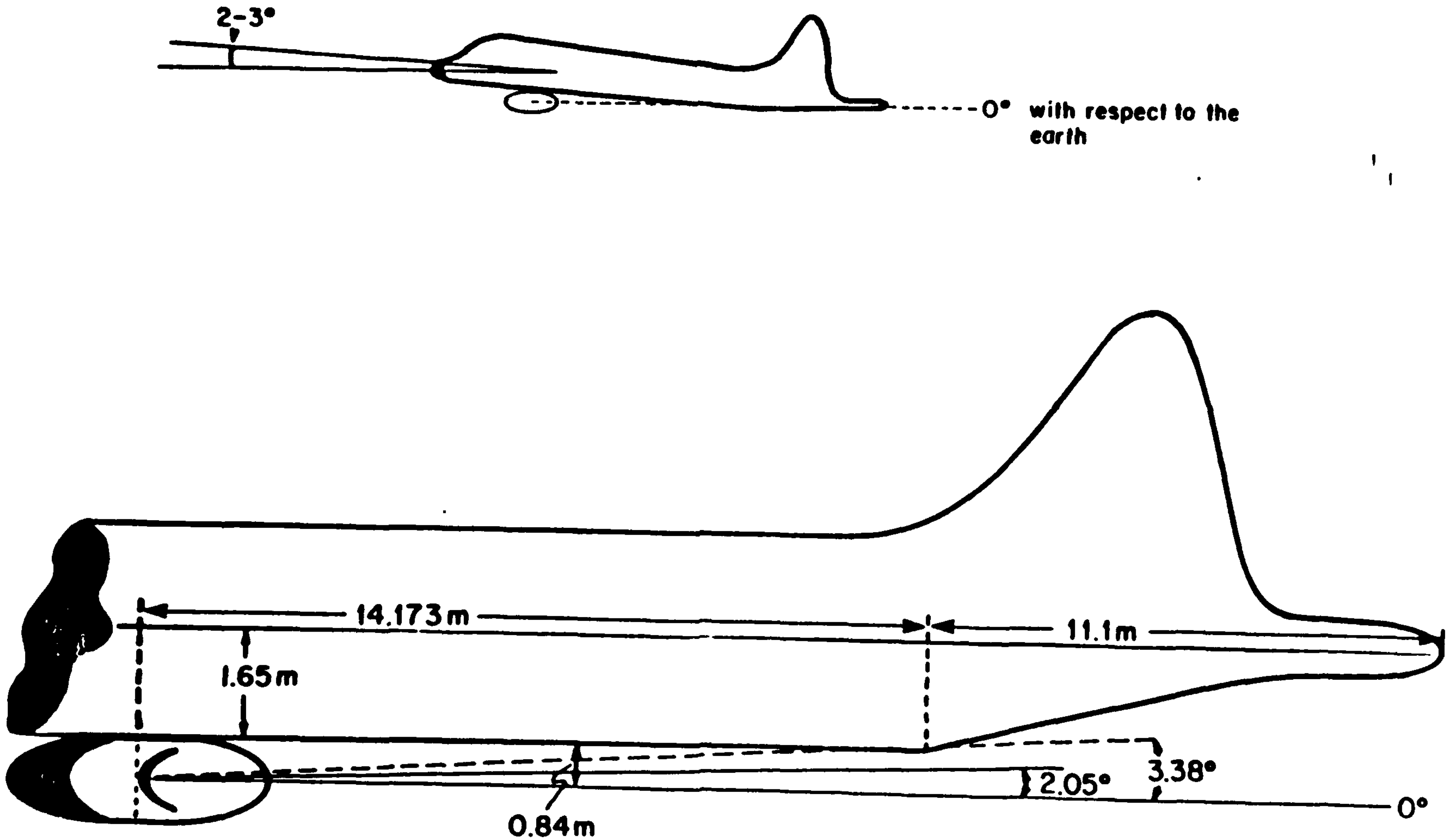

Fig. 6 Orientations of the lower fuselage radar on the NOAA WP-3D's in a normal "nose-up" flight orientation (top) and in level flight (bottom) to indicate beam blockage effects (provided by F. Marks).

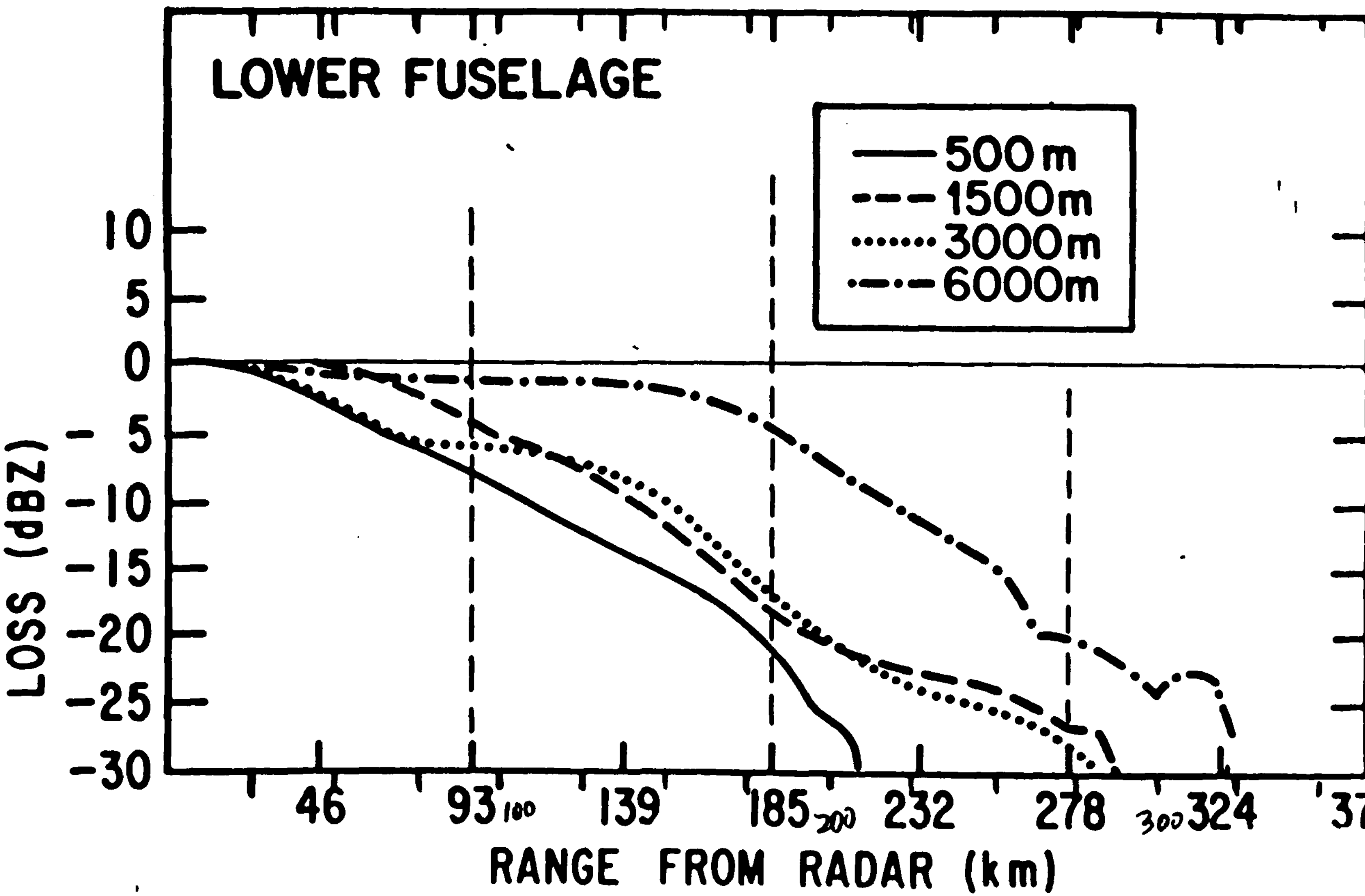

Fig. 7 Lower fuselage radar signal loss (dBZ) as a function of range from the radar for four flight altitudes: 500 m, 1500 m, 3000 m and 5000 m (provided by F. Marks).

e. Rawinsondes

The present rawinsonde stations in the western North Pacific region (Fig. 8) were described by LT Brian Williams (USN), who is a typhoon duty officer at JTWC. Relatively good coverage exists along the island chain between Taiwan and Japan. Although a number of stations occur along 10°N east of the Philippines, many of these stations have a single launch per day. Unfortunately, a large gap exists in the Philippine Sea where a majority of the tropical cyclones are found. Greg Holland suggested that rawinsonde launchers could be rented quite cheaply and placed on other islands, as was done in the Australian Monsoon Experiment during 1987.

Vin Lally of NCAR suggested that rawinsonde data could be obtained through a cooperative program with shipping companies that regularly transit the Philippine Sea. NCAR has developed a containerized shipboard unit that is presently used on Canadian ships. A single person is necessary to inflate and release the balloon. A microprocessor is used to automate the data collection and transmission aspects. Calculation of the winds could be via the cross-chain LORAN navigation system as in the dropwindsonde systems discussed above (Fig. 4). This is the principle of the CLASS soundings that were quite successful on land and on ships in the Genesis of Atlantic Lows Experiment (GALE) during 1986. ONR purchased three shipboard CLASS units for use in GALE. A shipboard CLASS unit will be taking observations during the Taiwan Mesoscale Experiment (TAMEX) in May 1987.

f. Wind Profilers

Nearly continuous wind observations through the troposphere can be obtained by wind profilers. Bill Frank described the four profiling radars of the Penn State University (Table 9). The 50 MHz (VHF) radars require a relatively large area (50 x 50 m) for the antenna, which appears to be a series of wires strung across a lattice of fence posts similar to a grape arbor. The 405 Mhz (UHF)

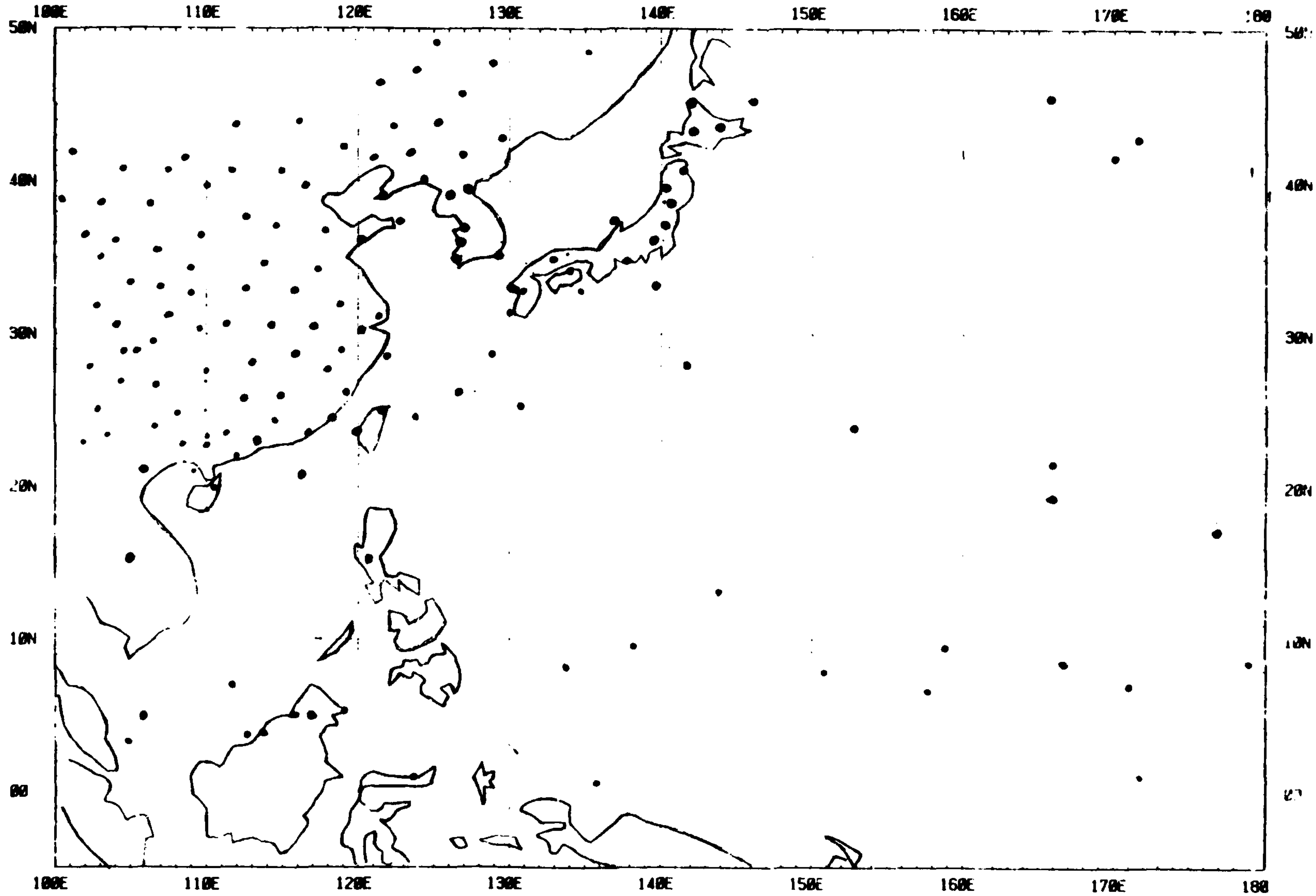

Fig. 8 Rawinsonde sites (dots) in the western North Pacific region during March 1987 (provided by B. J. Williams).

radar, which is similar to the 30 wind profilers that NOAA will be deploying in the central USA during 1989, does not normally acquire data as high as the VHF radar (~ 11.6 vs 16.8 km). However, the atmosphere in the region of tropical cyclones will probably contain inhomogeneities or cloud particles that will provide "scatterers" at higher elevations than 11.6 km. The 405 MHz (UHF) radar is able to observe winds closer (100-200 m) to the ground than the VHF (1 km). An example of the wind profiler observations at the Crown, PA site is shown in Fig. 9. Since hourly (much higher frequencies are available) observations are plotted, the normal 12-h rawinsonde launches would have provided only two or three observations during this interval.

As indicated in Table 9, one of the Penn State radars is "transportable". This radar is expected to be placed on an island in the western Pacific during the ONR field experiment. Another wind profiler (50 Mhz) is permanently located on the northern tip of Taiwan. Personnel of the Center for Space and Remote Sensing Research at the National Central University in Taiwan will be obtaining tropospheric wind profiles during the Taiwan Mesoscale Experiment in May 1987. Perhaps a third wind profiler may be available from the Naval Postgraduate School. A possible deployment strategy might be to place three (or more) profilers on islands in a "picket fence" arrangement that could provide continuous wind observations to the north of a tropical cyclone. Alternatively, a deployment in a triangular array may be used to monitor large-scale, high frequency divergence variations.

g. Surface Observations

Most ships avoid tropical cyclones, which contributes to the data deficiencies. Dr. Peter Black of HRD reported that three drifting buoys had been deployed by an aircraft in advance of Hurricane Josephine during 1984. These buoys had reported surface pressures, air and sea temperatures and 1-m

Table [illegible]. Locations and specifications of the wind profiling radars of Penn State University (provided by W. Frank).

Unit		Location
VHF I	"Shantytown"	15 km SSW of State College
VHF II	"Crown"	140 km NW of State College
VHF III	"Somerset" (under constr.)	140 km SW of State College
UHF I	Transportable	SPACE/MIST, FIRE, etc.

Radar	VHF	UHF
Frequency	49.8 MHz	404.37 MHz
Max Bandwidth	300 KHz	1 MHz
Min. Pulse Length	3.67 usec	3 usec
Antenna	**Co-Co**	**Co-Co**
Aperture	50 x 50 m	6.1 x 7.6 m
Beamwidth	4^{o}	4^{o}
Pointing Angles	Vertical and 14.72 orthogonal off-zenith	Vertical and 14.47^{o} orthogonal off-zenith
Range and Resolution		
Min. Height	1.02 km	100 - 200 m
Min. Height Resolution	290 m	100 m
Height Intervals	24	24
Max. Height (age)	16.8 km	11.6 km
Max. Velocity Resolution	0.31 m'sec^{-1}	0.29 m'sec^{-1}
Min. Temporal Resolution	90 sec	30 sec

wind speeds through the passage of the hurricane. Comparisons of the buoy data with a very limited set of aircraft overflights indicated standard deviations of 1.0 mb, 0.8°C and 1.8 m/s, respectively. The Josephine buoys also included a 200 m thermistor chain to observe ocean temperatures at four levels. Similar minibuoys to measure pressure, air and sea temperature are planned for a 1987 hurricane. Wind speed and subsurface temperature capability will be added to the minibuoys by 1988. LT Williams indicated that an array of drifting buoys will be tested in the Philippine Sea during 1987.

5. Objective Analyses

Each of the potential observational systems discussed above has different error characteristics. Several of these systems provide data at asynoptic times and irregularly in space. Consequently, a special analysis scheme is required to convert the variety of observations in one time and three spatial dimensions into a regular array for calculations. Dr. Steve Lord and James Franklin of HRD have recently completed a three-dimensional, nested analysis of wind fields in the environment of Hurricane Debby. The input data included Omega dropwindsondes, rawinsondes, USAF reconnaissance and satellite-derived winds. The basic analysis tool combines a two-dimensional least-squares fitting algorithm with a derivative constraint that acts as a spatial low-pass filter. Separate analyses on many pressure surfaces are combined into vertical cross-sections to produce vertical continuity. The final wind analyses were used to diagnose the leading terms in the vorticity equation and as initial conditions for a barotropic track prediction model. This research wind analysis produced a substantial reduction in track error for short-term (12-24 h) forecasts, which was primarily due to an improved representation of the wind field within 500 km of the storm center.

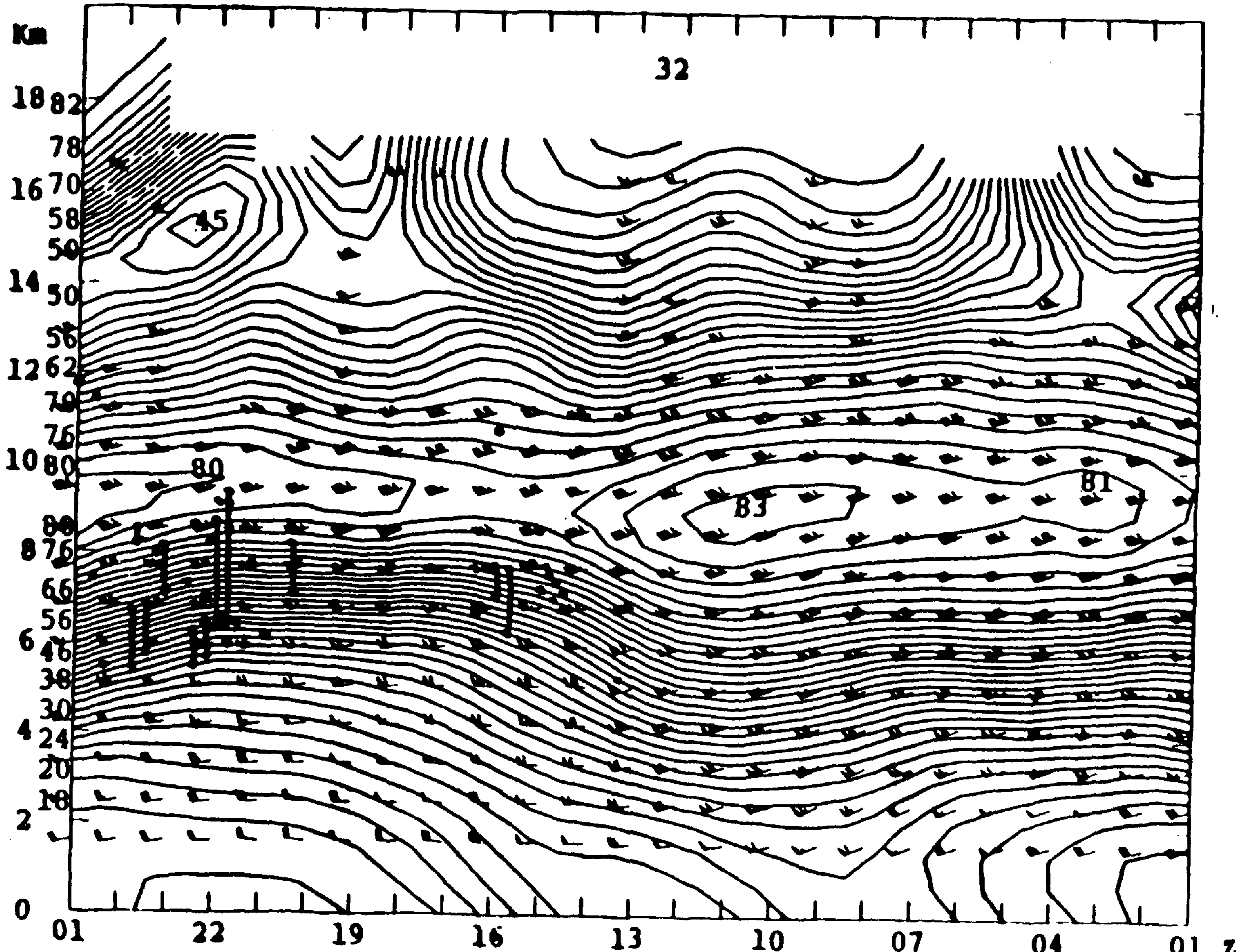

Fig. 9 Hourly observations of wind speed (kt) and direction observed at the Crown, PA wind profiler site of Penn State University. Time increases from right to left and the contour interval is 3 kt. Locations of reported turbulence by aircraft are indicated by the vertical lines (provided by W. Frank).

6. Future ONR Plans

a. Issues to be Explored

As indicated in Fig. 1, this workshop represents an early stage in the planning for the ONR field experiment. During the upcoming second phase, both observational and theoretical studies will continue. The study of operational scenarios by Sandgathe is expected to be completed by August 1987. Dr. Bill Gray and associates at Colorado State University are examining the existing aircraft reconnaissance (and rawinsonde) data from western North Pacific tropical cyclones. These studies are expected to illustrate what questions regarding tropical cyclone motion can be answered with existing data, and possibly what additional data may be required. Meanwhile, theoretical studies that are in progress by several groups are expected to generate testable hypotheses. It is essential that these observational and theoretical studies be advanced somewhat before the four options described in the Introduction are brought to a final resolution.

An important aspect in the planning for a North Pacific (or an North Atlantic) field experiment is to explore the availability of resources. As mentioned above, the possible deployment of the NOAA WP-3D's in a Pacific experiment is a crucial question. Although the HRD could be assured of a large number of tropical cyclones in the western North Pacific for the types of studies described in Section 3a, there are additional costs associated with operating in the Pacific rather than in the Atlantic. A more basic question is whether the WP-3D's are completely unavailable because of a requirement to serve as a "backup" reconnaissance aircraft throughout the Atlantic hurricane season.

Another crucial question is the availability of other aircraft to serve as observing platforms and to deploy instruments. The pending withdrawal of USAF reconnaissance aircraft in the western North Pacific is obviously a

serious hindrance to the field program. A possible replacement reconnaissance aircraft may be available from Australia on a contract basis. Costs for replacing the USAF reconnaissance flights in the inner core are unknown. It should be noted that other USAF weather squadrons (and U.S. Navy aircraft) do fly missions in the North Pacific region (outside of tropical cyclones). These aircraft might be outfitted to acquire dropwindsonde data in the environment of tropical cyclones. Even jet aircraft regularly flying between Guam and Japan or the Philippines might be able to acquire dropwindsonde data.

International participation in a North Pacific experiment is another aspect that needs to be explored. Availability of data from the Japanese Geostationary Meteorological Satellite needs to be established. A state-of-the-art wind profiler is located at the Kyoto University Radio Atmospheric Science Center. Japan already has an excellent rawinsonde network that might be augmented during a field experiment. Similarly, the rawinsonde network of the People's Republic of China (PRC) or other Asian nations might be augmented. The PRC also has oceanographic ships that have rawinsonde capability. Although scientists in many Asian nations are aware that an experiment was being planned for 1989, the details and the opportunities for participation have not been explained to these scientists or key government decision-makers.

b. Possible North Atlantic Experiment

One of the objectives of the workshop was to examine possible cooperative studies between HRD and ONR. Based on informal discussions only, the following "strawman" is suggested as an example of the cooperative studies that might be explored if a decision is made to move the field experiment from the western North Pacific. During 1989, both of the WP-3D's are expected to be equipped with Doppler radars. The HRD is proposing to use these airborne Dopplers to acquire data sets to do complete budget studies of the inner core

of a hurricane. A possible role for ONR would be to simultaneously acquire environmental data using LORAN-based dropwindsondes of the type to be used in ERICA earlier in 1989. The objective would be to obtain the most complete data sets ever for tropical cyclone research. This data set would be adequate for tropical cyclone motion studies since environmental data would be acquired without neglecting possible internal interactions. Meanwhile, the participation of ONR in acquiring environmental data would provide HRD scientists the synoptic setting necessary for interpreting (and extending) their inner core budget studies.

This strawman proposal can be explored during the phase II of Fig. 1. The basic questions to be addressed relative to each proposed hypothesis are: (i) Given that an adequate data set does not presently exist, would the data set provided by the proposed cooperative study be adequate to test the hypothesis? (ii) Would such an experiment be directly applicable to the significant tropical cyclone track prediction scenarios discussed in Section 3b?

c. Tentative Schedule

The next meeting of the ONR group is expected to be during autumn 1987. Although originally envisioned as an adjunct to the IUGG meeting in Vancouver, British Columbia, other possible sites (and times) are being considered. The primary agenda will be to discuss the results of the observational and theoretical studies. Hopefully, some tentative hypotheses will be presented for discussion. Meanwhile, further information on observational platforms and instruments will be gathered.

In considering the four options posed by Dr. Abbey (see Section 1), the most basic question is whether a field experiment is even needed. It should become clearer after the August 1987 meeting whether the answer (based on tentative hypotheses presented) is yes. If the answer is yes, the question of

whether the field experiment should remain in the Pacific or be shifted to the Atlantic must be addressed. International and/or other national institutional/agency support must be available if a meaningful experiment is to be carried out in the Pacific. These questions must be answered by January 1988 if an orderly and effective planning cycle as suggested in Fig. 1 is to be achieved. Hopefully, the participants in this workshop and others interested in the study of tropical cyclone motion will provide input to the decisions.

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8. Acknowledgements

Dr. Stan Rosenthal of HRD agreed to host the workshop. Howard Friedman and Juanita Simpkins of HRD assisted in the arrangements. Participation by the author, S. A. Sandgathe and B. J. Williams was funded by the Office of Naval Research through the research contract entitled "Tropical Cyclone Motion Studies" (Program Element 61153N). Mrs. Penny Jones ably typed the drafts of the manuscript.

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AGENDA

6 April 19[illegible]

JOINT HRD AND ONR WORKSHOP ON
OBSERVATIONAL SYSTEMS FOR TROPICAL CYCLONE STUDIES

I. INTRODUCTORY REMARKS
- Overview of the HRD [S. Rosenthal]
- Background of ONR initiative on Tropical Cyclone Motion [P. Abbey]

II. PURPOSE (objectives of joint workshop)

III. OBJECTIVES OF OBSERVATIONAL STUDIES
- HRD plans (1987-1990) [R. Burpee]
- ONR cyclone motion studies (preliminary)
  - Hypotheses from theoretical planning meeting [R. Elsberry]
  - Overview of some western Pacific situations [S. Sandgathe]

IV. SYNOPSIS OF POTENTIAL OBSERVING SYSTEMS
- A. Dropwindsondes - Present and future [J. Franklin; V. Lally]
- B. Satellite-sensed winds, T and q [C. Velden]
- C. Airborne systems [OAO, NCAR ?]
  1. Radar (conventional and Doppler) [F. Marks]
  2. Wind (Flight-level and surface) [P. Black]
  3. Other parameters
- D. Rawinsonde
  1. Conventional (WPAC) [B. Williams]
  2. CLASS (land and shipboard) [V. Lally]
- E. Ground-based profilers (wind, T,q) [B. Frank]
- F. Buoys [P. Black]
- G. Analysis schemes for multiple data sources in T.C. [S. Lord]

V. OPEN DISCUSSION
- A. Possible cooperative studies or conflicts if ONR field experiment is (1) in Pacific or (2) in Atlantic
- B. Possible "piggyback" experiments
- C. Factors to be resolved
  Availability of observing platforms/systems
- D. Comments by potential participants

APPENDIX B

LIST OF PARTICIPANTS

Name	Affiliation
Russ Elsberry	Naval Postgraduate School
Scott Sandgathe	USS Carl Vinson
Brian Williams	Joint Typhoon Warning Center
Raymond Zehr	NOAA/NESDIS/Colorado State
Vincent E. Lally	NCAR
Chris Velden	Wisconsin/CIMSS
Greg Holland	Bureau of Meteorology Research Centre
Tom Gerish	NOAA/Office of Aircraft Operations
Chip Guard	HQ Air Weather Service/DNT
A. Barry Damiano	NOAA/OAO
Robert Merrill	University of Wisconsin/CIMSS
Jeff Masters	NOAA/OAO
Peter Black	NOAA/HRD
Ted Tsui	NEPRF
Simon Chang	NRL
Bill Gray	Colorado State University
Hugh Willoughby	HRD
Roger Smith	Monash University
Lloyd Shapiro	HRD
John Ward	NOAA/NMC
Edwin Nunez	Nichols Research Corporation
Herbert Hunter	Nichols Research Corporation
Edward Rodgers	GSFC/NASA
Boyce R. Columbus	AFGWC/WFMP
Charles Holliday	AFGWC/WFMP
Stephen Lord	HRD
Charles Neumann	Retired
Arthur Pike	NOAA/NHC Miami
Mike Fiorino	Fleet Numerical Oceanography Center
Dave Parrish	NOAA/NMC
Bill Frank	Pennsylvania State University
John Molinari	SUNY/Albany
Frank Marks	NOAA/AOML/HRD
Paul Willis	NOAA/AOML/HRD
James Franklin	NOAA/AOML/HRD
Howard A. Friedman	NOAA/AOML/HRD
Jerry Jarrell	SAIC Monterey
Stan Rosenthal	HRD
John Lewis	National Severe Storms Lab
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